Searching for the Polycentric City: A Spatio-temporal Analysis of Dutch Urban Morphology

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Searching for the polycentric city: a spatio-temporal analysis of Dutch urban morphology

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SUMMARY

A new methodology is presented that describes the density of urban systems. By combining highly detailed height measurements with amongst others topographical data we are able to quantify the urban volume. This new approach is tested in two separate case-studies that respectively relate to the temporal and spatial dimension of the urban environment. In the first study the growth of the city of Amsterdam over the past century is studied. The urban volume indicator is used to visualise and quantify the urban extension and intensification process. To critically analyse the spatio-temporal development of Amsterdam the self-organizing map approach is applied. Special attention is given to highlighting any signs of recent polynuclear development. The second case-study compares the spatial distribution of high-density zones of the four major Dutch cities

KEYWORDS: *urban morphology, urban volume, density, indicator, self-organizing maps*

INTRODUCTION

The urban landscape is continuously changing. Sub-urbanisation and urban sprawl have altered the classical monocentric city and given rise to new polycentric urban forms that have for example been described as edge-cities (Garreau 1992). Although the decline of traditional city centres in Europe does not nearly resemble the many North American examples, cities here also show a growing importance of its sub centres (e.g. Gaschet 2002 and Martori i Cañas et al. 2002). The Dutch Randstad area, the constellation of the four biggest cities in the western part of the country, is now generally acknowledged as being an interdependent network-city (VROM 2001) in which the various urban sub centres are functionally related. This changing urban landscape calls for new forms of urban planning that put less emphasis on the original city centres. A thorough understanding of the current urban processes can help formulating new city policies.

The most notable urban developments occur within the current urban areas and are difficult to trace with classical geographical analysis that typically focuses on urban spread in two dimensions. The intensity in which the land is used is normally difficult to assess. Recent studies on urban density (e.g. Longley and Mesev 2002) have applied detailed individual address point data to characterise intensities in land use. These data-sets may however fail to incorporate the relative importance of individual locations. Without additional data (such as applied by Maat en Harts 2001) they do not recognise the importance of large, tall buildings that characterise high-density zones and that are extremely important in terms of their number of inhabitants, employees or visual dominance. The analysis of the third (height) dimension of urban morphology is scarce however, mainly due to limited data availability. Incidental examples reflect a painstaking data-collection process (e.g. Frenkel 2004).

This paper presents the results of a detailed analysis of the third dimension of current Dutch cities that makes use of the recently released extremely detailed height information of the Netherlands. This new data-set allows for the relatively easy creation of an urban volume layer that effectively captures urban morphology. Building volume is taken here as a proxy for urban density. This approach has the advantage of closely resembling the human perception of urban density (Fisher-Gewirtzman et al. 2003) and its results are therefore easily interpreted. The newly developed urban volume methodology is applied in two separate case studies that respectively have a temporal and a spatial dimension. Time is the crucial element in the study that deals with historic development of urban density in the city of Amsterdam in the 1900-2000 period. An important element in the analysis of the temporal dimension is the application of the self-organizing map method to help distinguish spatio-temporal relations in our rich data-sets. The spatial dimension is the subject in a second application that compares the density distribution of the four major Dutch cities.

METHODOLOGY

The urban volume indicator that we apply in our analysis is based on the combination of land use and height data. The most crucial data-set in this analysis is the newly developed Dutch national elevation data-set (Actueel Hoogtebestand Nederland) which has become available in 2003. This highly detailed data-set was collected over the past seven years under the supervision of the Survey Department and is based on laseraltimetric measurements. It has a height precision of about 15 cm standard deviation per point and an average point density of 1 point per 16 m^2 or better (Oude Elberink et al. 2003). Huising and Gomes Pareira (1998) offer a full discussion of the intricate problems that occur and that are dealt with in the pre-distribution phase of laser-height data. The elevation data thus has enough spatial detail to distinguish individual houses and gives a detailed account of their heights. For this study we use a rasterised version of the original point-data-set with a 5x5 m pixel resolution that provides an average value of all height points within the gridcell. For the rare cases that a gridcell is lacking information (e.g. in the case of a missing overlap in the original data strips) a combination of mathematical techniques is used to fill in the gaps (Vosselman & Maas 2001). Only the larger waterbodies completely lack height information because of their reflecting characteristics. These do not pose a problem in our analysis because we are focussing on the built-up areas.

To select only the heights of buildings an overlay is made with a thematic layer that contains information on land use. A detailed topographical map (top10vector, see TDN 1998) that distinguishes various building-types is used for this purpose. This procedure makes sure that non-urban elevated objects such as trees and infrastructure are not included in our analysis of urban volume. A first step in the creation of the urban volume data layer is the calculation of the actual building heights by subtracting a reconstructed ground level height from the original building heights that referred to the national datum level (0 m or mean sea level). In a second step the occasionally missing extreme high height values are added from an additional websource (skyscrapers.com). The gridcell values are then multiplied by their surface area (25 m^2) in order to represent a volume-per-pixel of buildings. This high resolution provides an extremely detailed, but also very heterogeneous and dispersed account of urban volume. The results are therefore generalised to allow for a more easy interpretation of the urban volume indicator. This is done by an aggregation to a 25 m grid in which the aggregate volume of the original 25 cells is retained. A full account of the applied methodology and data-sets can be found in: Koomen et al. (2004) and Kaufholz (2004).

Self-organizing maps

The self-organizing map (SOM) approach that is used in the first case-study can be described as a visualisation and analysis tool for high dimensional data, but they have also been used for clustering (Vesanto and Alhoniemi 2000), dimensionality reduction, classification, sampling, vector quantization, and data-mining (Kohonen 2001). The fundamental idea of a SOM is to map the data patterns onto an n-dimensional grid of segments or units. This mapping tries to preserve topological relations, i.e., patterns that are close in the input space will be mapped to segments that are close in the output space, and vice-versa. Each segment, being an input layer segment, has as many weights or coefficients as the input patterns, and can be regarded as a vector in the same space as the patterns. When training or using a SOM with a given input pattern, the distance is calculated between that pattern and every segment in the network. The segment that is closest to the winning segment is selected, and then the pattern is mapped onto that segment. If the SOM has been trained successfully, the patterns that are close in the input space will be mapped to segments that are close (or the same) in the output space, and vice-versa. Thus, SOM is "topology preserving" in the sense that (as far as possible) neighbourhoods are preserved through the mapping process.

Before training, the segments may be initialised randomly. Usually the training consists of two parts. During the first part of training, the segments are "spread out", and pulled towards the general area (in the input space) where they will stay. This is usually called the unfolding phase of training (Kohonen 2001). After this phase, the general shape of the network in the input space is defined, and we can then proceed to the fine tuning phase, where we will match the segments as close as possible to the input patterns, thus decreasing the possible error.

The basic SOM learning algorithm may be described as follows:

Let

w_{ij}	be the weight vector associated with a segment positioned at column *i* row *j*
x_k	be the vector associated with pattern k
d_{ij}	be the distance between weight vector w_{ij} and a given pattern.
h	be a neighbourhood function described below
A	be the learning rate also described below.

For each input pattern then take the following steps

1) Calculate the distance between the pattern and all segments of the SOM with:
   $d_{ij} = \| x_k - w_{ij} \|$ (this is called the calculation phase)
2) Select the nearest segment as winner wwinner:
   $w_{ij} : d_{ij} = \min(d_{mn})$ (the voting phase)
3) Update each sgment of the SOM according to the update function:
   $w_{ij} = w_{ij} + Ah(wwinner,w_{ij}) \| x_k – w_{ij} \|$ (the updating phase)
4) Repeat the steps 1) to 3), and update the learning parameters, until a certain stopping criterion is met.

This algorithm can be applied to a SOM with any dimension. The learning rate A must converge to 0 in order to guarantee convergence and stability for the SOM (Kohonen 2001). The decrease from the initial value of this parameter to 0 is usually done linearly, but any function may be used. The neighbourhood function h assumes values in [0,1], and is a function of the position of two segments (a winner segment, and another segment), and radius. It is large for segments that are close in the output space, and small (or 0) for segments far away. Usually, it is a function that has a maximum at the centre, monotonically decreases up to a radius *r* (sometimes called the neighbourhood radius) and is zero from there onwards. For the sake of simplicity, this radius is sometimes omitted as an explicit parameter. The two most common neighbourhood functions are the bell-shaped (Gaussian-like) and the square (or bubble), in both cases, we force $r \rightarrow 0$ during training to guarantee convergence and stability. The update of both, the learning rate and the neighbourhood radius, parameters may be done after each training pattern is processed or after the whole training set is processed.

SPATIO-TEMPORAL ANALYSIS OF THE AMSTERDAM URBAN VOLUME

The capital of the Netherlands provides an especially interesting case study area because its urban landscape has changed significantly in the past century. After almost two centuries of stagnation the city started to grow rapidly in the last part of the 19th century, reflecting a late catch-up with the industrial revolution. This period is still notable as an urbanisation ring around the historic centre. From the beginning of the 20th century urban expansion has been steered through municipal town planning, initially resulting in the addition of extensive new neighbourhoods to especially the southern and western edges of town and the first major construction north of the central riverfront. After a disruption during the Second World War, extensive garden villages were added to the western and southern limits of town in the 1950-1970 period, following the 1935 general extension plan (van der Cammen et al. 1988). The latest major additions to the city- layout can be found in the south-east, where a completely new 100.000 inhabitants neighbourhood was constructed, and attached to the western and northern extremities of town. Large-scale inner-city redevelopment started in the 1980's and consists mainly of residential construction on the former maritime and industrial centre on the south-east shore of the riverfront. Several high rise commercial areas have recently sprung up around the relatively young ring road. Concentrations of office building with maximum heights of up to 150 m have been constructed at the western, southern and south-eastern parts of town and around a more centrally located railway-station. Amsterdam thus starts to get a polynuclear appearance. Our study aims at visualising and quantifying these urban changes by reconstructing the urban volume of 1900-2000 period.

The historic urban volume is reconstructed by combining the original 2000 urban volume data layer with a detailed data-set that includes the year of construction of all individual buildings in the municipality of Amsterdam. The latter point data-set is combined with a detailed topographical data-set that contains building outlines. This enriched polygon map is then rasterised to allow for the recreation of the urban surface in any chosen time-period. By for example selecting all cells that relate to buildings that were built in or before 1910 we arrive at reasonable reconstruction of the historic urban area at that time. This reconstructed historic urban area map allows for the extraction of those gridcells in the urban volume data-set that were supposedly built-up in 1910. This rough approach has of course some limitations. Old buildings may have been replaced by newer ones in the past 100 years, as the most recent construction year replaces any previous information on an edifice in our data-set. These locations will erroneously be left out of the 1910 analysis, introducing an underestimation of the urban volume in that time-step. The opposite may also be true: the applied building outline polygons describe urban blocks that are separated by streets or other open spaces. Especially in the old centre these areas may contain many individual buildings. As the oldest building year is assigned to the total block, recent volumes will be incorrectly related to older edifices, introducing an urban volume that might deviate from the original one. Visual inspection of the historic urban area map however shows the old parts of town as more or less continuous surfaces with a relatively homogenous volume distribution, indicating that the described limitations only affect isolated locations. Moreover the reconstructed urban area maps correspond well with historic maps of the Amsterdam area (e.g. Wolters-Noordhoff 1988). Since our analysis is mainly meant to explore the possible use of the urban volume indicator we do not consider these drawbacks to be serious constraints to our analysis.

Historic urban volume maps were created for every decade since 1900. A selection of the most crucial time-steps is represented in Figure 1. The figure shows the above average volumes per gridcell, the values in these graphs are classified according to their standard deviation from the mean. It thus shows all high volume areas with the exceptionally high values in the darkest colours. The time series reflects the continuous growth of the city in all directions following the large-scale pre-war (1940) and post-war (1970) extensions. It furthermore highlights the recent, erratic spread of high intensity zones throughout the city. The 2000-urban volume map shows an abundance of high volume zones in almost all neighbourhoods of the city, clearly indicating a deviation from the original monocentric form.

Applying the self-organizing maps approach

In order to improve the analysis of the spatio-temporal patterns a SOM-approach was applied. A relatively large SOM with 60 segments was set up to isolate the areas of growth in volume with a certain degree of precision. Each input data vector, a gridcell, was composed of seven variables: the volume values for the years 1910, 1940, 1970 and 2000 and distances to the ringroad, the nearest station and the historic city centre.

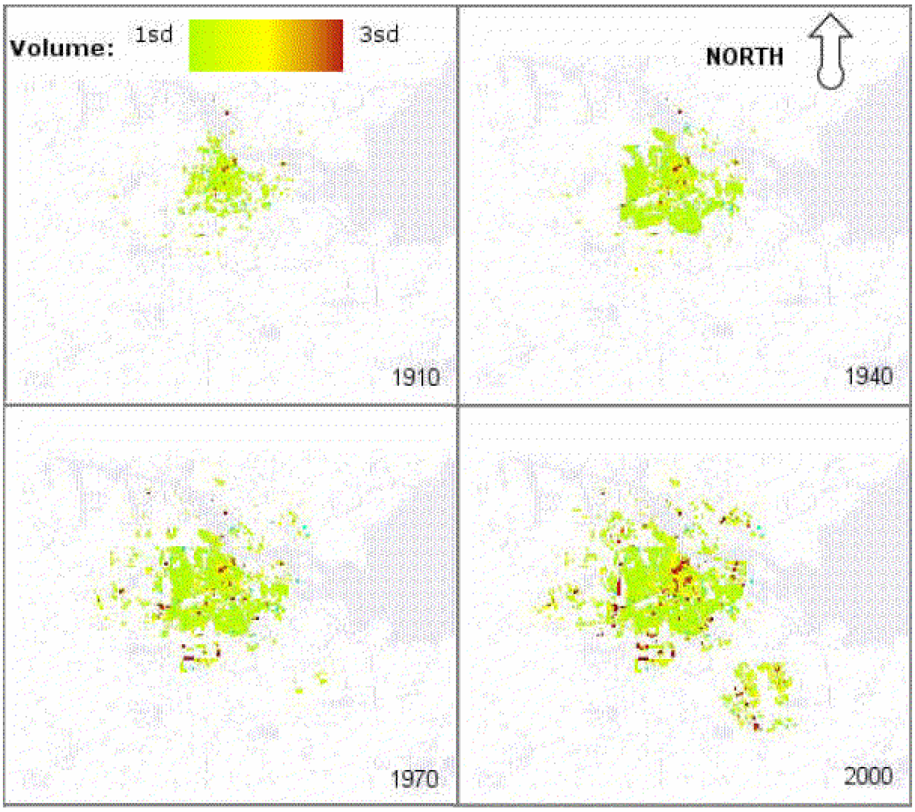

Figure 1 Reconstructed urban volume in the city of Amsterdam for the years 1910-2000

Table 1 gives an overview of the 23 SOM- segments relating to urban development. The missing segments have an average urban volume of less then 1250 m^3 (equivalent to an average building-height of 1 meter in the 25x25m cell) and are thus considered not to be important for our study. The segments characterise homogenous groups of gridcells that share a common development history and relative location to key features of the city. The analysis clearly distinguishes the subsequent development phases. The first seven rows for example refer to the last stage of urban development in the 1970-2000 period. The low-density developments of segments 29 and 30 can be found far from the original city centre; these correspond with the recent construction of low-density single-family dwellings at the western extremities of town. The high-density developments near the stations of segment 42 represent the recent construction of extremely high office buildings. The 1940-1970 period shows urban developments at 4 to 7 km from the city centre. Several low-density developments (segments 39 and 40) are located near the ringroad. The 1910-1940 extensions can be found at an average distance of 2 to 3 km from the centre, with the highest densities near the stations (segment 54). The oldest parts of town are described in the last four segments, with the highest densities in segment 60 within 1.5 km from the Dam Square near where the city was founded.

Some of the most notable SOM-segments are mapped in Figure 2. This selection consists of the highest densities per building period, each reflecting the different characteristics of the relative high rise developments in that period. The oldest developments (segment 60) only have a medium density but cover an extensive area. Isolated areas of higher density of the 1910-1940 and 1940-1970 period can be found within (segment 48) and outside the ringroad (segment 54) respectively. By far the highest densities date back to the last building phase and are found near the stations (segment 42).

Segment	Volume 2000	Volume 1970	Volume 1940	Volume 1910	Distance to centre	Distance to ringroad	Distance to station
38	**1769**	118	2	1	4342	**699**	1034
50	**2114**	157	67	13	2156	2506	1531
29	**3064**	0	0	0	**7188**	2429	1336
30	**4449**	1	0	0	**9071**	4003	2019
35	**4922**	5	3	2	3489	1517	1619
36	**10213**	11	6	4	5013	1910	1408
42	**34249**	0	0	0	5901	2077	**862**
39	1533	**1528**	1	1	4361	**918**	**999**
34	2265	**2259**	25	20	6669	2955	2485
40	3017	**3011**	2	2	4250	**924**	1307
41	4650	**4639**	5	5	4387	1385	1424
47	7755	**7714**	1	0	4953	1560	1353
48	15223	**15187**	3	0	4704	1305	1477
45	1792	1785	**1784**	7	3149	1142	1263
51	2400	2368	**2365**	28	2262	2245	1338
46	3095	3093	**3093**	6	3009	1167	1230
52	4291	4288	**4288**	10	2785	1398	1268
53	6326	6321	**6321**	15	2410	1782	1333
54	15324	15324	**15324**	9	1832	2349	**900**
57	2326	2269	2263	**2229**	2266	2080	1457
58	3753	3739	3732	**3714**	1968	2197	1477
59	5629	5625	5622	**5618**	1727	2411	1513
60	10037	10034	10034	**10033**	**1459**	2740	1478

Table 1 Selection of SOM analysis results relating to the historic development of Amsterdam; characteristic results are indicated in bold and are discussed in the text.

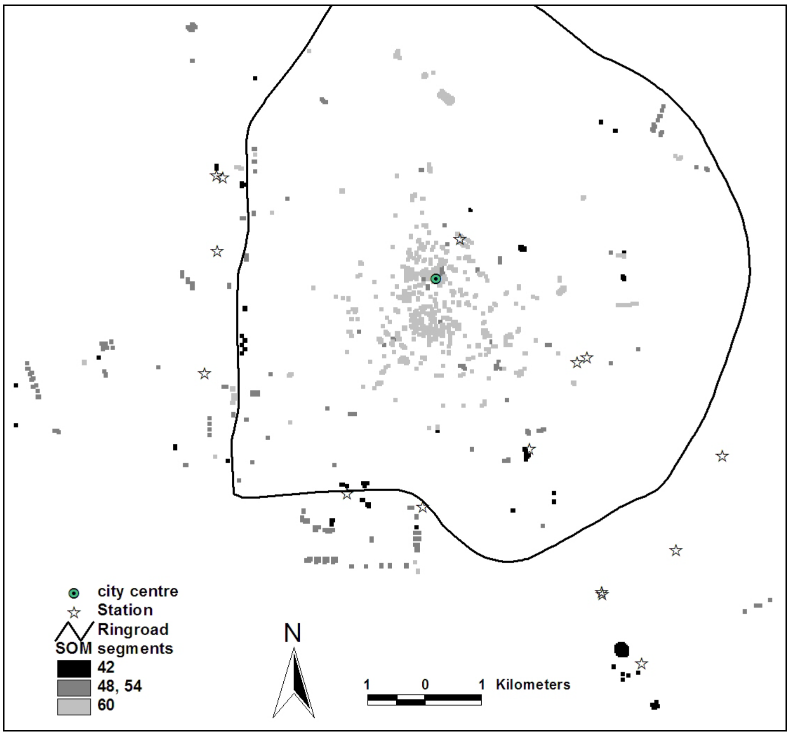

Figure 2 Selection of SOM segments reflecting high-density developments of different time-periods.

SPATIAL COMPARISON OF THE FOUR MAJOR DUTCH CITIES

The second case study in our analysis aims at comparing the urban volume patterns of the four major Dutch cities: Amsterdam, Rotterdam, the Hague and Utrecht. These cities are part of the metropolitan Randstad region in the west of the Netherlands, but differ in their history and layout. Amsterdam is the largest city of the country in terms its number of inhabitants and has a large well-preserved historic centre. Rotterdam covers the largest surface area, mainly as a result of its vast harbour area. Its centre was heavily bombed in the Second World War and it was almost completely reconstructed in the 1950's. The Hague is a relatively new city that houses the Government, most ministry buildings and a large number of offices. Utrecht is the smallest of the four cities, both in terms of its population and size. It is the only city that dates back to before 1000AD and it still retains part of its medieval building history. Our analysis describes the different layouts of the cities and specifically looks for indications of polycentric patterns.

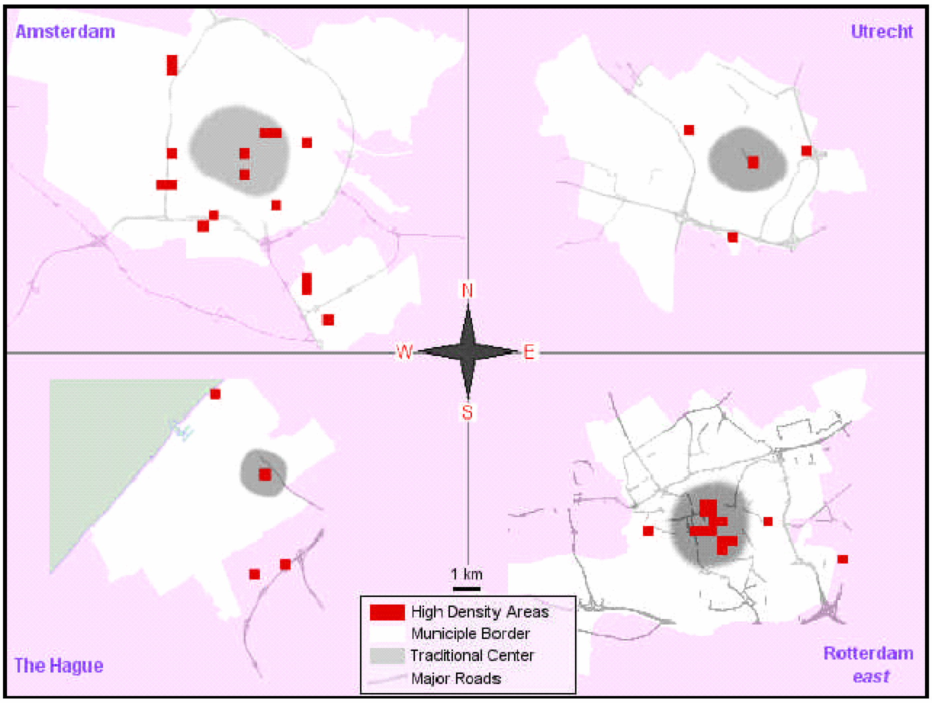

Figure 3 High density patterns of the four major Dutch cities at 500 m grid level

To visualise the density patterns a filtering operation was applied on the original urban volume layer. By reducing the original 5 m resolution to a 500 m grid using a maximum filter we are able to highlight the areas with highest densities. This approach puts a strong emphasis on the observed maximum values, which is in line with the visual dominance of tall buildings, but it may overestimate their actual contribution to the total urban volume. Figure 3 shows the areas with the highest (over three standard deviations) urban volume values per city. Since these values are relative to the mean urban volume value per city, the figure only indicates the areas that have a high density in relation to the average density of that city. So we cannot compare the densities between cities in an absolute sense, but we are able to distinguish local density patterns. These patterns are different for each city. Amsterdam and Rotterdam have the most high-density zones, but the highly erratic pattern of Amsterdam contrasts strongly with the concentrated pattern in Rotterdam. The Hague and Utrecht seem to have a more homogenous distribution of densities and offer less extremely high values. Both cities have a high-density area within its traditional centre as well as several high-density areas outside that centre. Out of the studied cities only Rotterdam seems to be a truly monocentric city. Amsterdam offers by far the most varied cityscape.

CONCLUSION

The proposed urban volume indicator provides an adequate characterisation of the actual physical appearance of the city in time and space. What is more: the quantitative description allows for an objective, highly detailed statistical analysis of urban patterns. The spatio-temporal analysis of the urban development of the city of Amsterdam combines the urban volume indicator with other equally-detailed base-data. This study provides interesting insight in the making of the city. The gradual, lateral extension is clearly mapped, but the analysis also shows the growing importance of numerous high-density zones throughout the city. This finding is further quantified in the related SOM-analysis. The SOM results also indicate the addition of isolated high-density zones to the historic medium-density city centre in the past century. This approach furthermore proves the recent emergence of small, but extreme high-density developments near stations at a large distance from the centre.

The urban volume indicator is also useful for characterising the differences in urban density in the four major Dutch cities. This initial study shows a distinction between cities in which high-density areas are concentrated in the original city centres (Rotterdam and the Hague) and cities that show these areas at a considerable distance from the centre (Amsterdam and Utrecht). The latter cities clearly have a polycentric appearance. The layout of major Dutch cities thus reflects evidence of opposing centripetal and centrifugal forces. The urban volume indicator can help visualise and quantify the impact of these forces, thus providing useful input to the ongoing debate on urban (re)development.

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